SIMULTANEOUS MEASUREMENTS ON THREE SATELLITES

AND THE OBSERVATION OF THE GEOMAGNETIC TAIL AT 1000 R_E

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Abstract

During the last week of September 1966 the heliocentric orbiting spacecraft Pioneer 7 was behind the earth in a position to observe the geomagnetic tail between 900-1050 R_E. At the same time Explorer 28 and Explorer 33 were monitoring the interplanetary medium and the magnetosheath near the earth. Comparison of these simultaneous magnetic field measurements permits the isolation of intervals when Pioneer 7 is observing steady, enhanced-magnitude solar or anti-solar directed fields characteristic of the extended geomagnetic tail which are different from the interplanetary fields convecting past the other two spacecraft. The occurrence of approximately 10 intervals of tail observation of duration from a few minutes to several hours is interpreted as a sweeping of the tail across the spacecraft as the tail responds to variations in the direction of plasma flow. Discontinuous features in the interplanetary magnetic field are also found to convect past the three spacecraft with velocities which compare well with interplanetary solar wind velocities measured by the Vela satellites at the same time. Field magnitudes near the tail at 1000 R_E are found to be weaker than the corresponding interplanetary field as is predicted by the magnetogasdynamic theory.

I. Introduction

The interplanetary probe Pioneer 7 was launched on August 17, 1966, in a trajectory which brought the spacecraft into the region near the earth-sun-line almost 1000 R_E (earth radii) behind the earth during the last week of September 1966. Pioneer 7 was then in a position to search for the possible existence of the geomagnetic tail or other effects associated with the interaction of the solar wind plasma with the geomagnetic field.

The earth's magnetic tail (Ness, 1965) had previously been shown to exhibit well-defined structure at distances up to 80 R_E behind the earth with the Explorer 33 spacecraft (Ness et al., 1967; Behannon, 1968; Mihalov et al., 1968), but no evidence for the tail was found at 3300 R_E by Mariner 4 (Van Allen, 1965). In a previous analysis of Pioneer 7 magnetometer data in this region behind the earth, Ness et al. (1967b) noted several intervals when the magnetic field assumed the typical tail-like solar or anti-solar orientation and enhanced, steady magnitudes for brief intervals of the order of an hour's duration. These authors interpreted the data as the probable observation of the tail, but the short duration and infrequent occurrence of the intervals were in contrast to the much longer time invariant observations made nearer the earth. These authors pointed out that the observed non-radial flow of the solar wind (Strong, 1968; Wolfe et al., 1966) of up to 5° to 10° would produce corresponding changes in the tail orientation and possible sweeping of the tail across the spacecraft. Alternatively, they suggested a more time invariant filamentary tail as a possible explanation for the measurements.

Plasma data from Pioneer 7 (Wolfe et al., 1967) revealed intermittent intervals of anomalous plasma spectra and occasional disappearance of the plasma during the period that the spacecraft was behind the earth. These phenomena were attributed to the solar wind geomagnetic interaction effects, but again the absence of longer intervals with no detectable plasma was in contrast with the presence of longer intervals without plasma in the tail near the earth. These authors suggested the term "wake" as descriptive of an interaction effect without a clear, well-developed, time-invariant tail.

Comparison of simultaneous measurements by other experiments and other spacecraft furnishes additional information concerning the structure of the tail at 1000 R_E. The primary difficulty in independently interpreting the Pioneer 7 magnetic field observations is in knowing which features are associated with the earth and which are associated with the interplanetary fields being convected away from the sun. Although the average interplanetary field makes an angle of 45^{o} with the tail-like solar or anti-solar orientations, large variations from the average direction are frequent and the possibility of interpreting interplanetary data as geomagnetic tail data exists. One method of overcoming this difficulty is to compare the Pioneer 7 results with simultaneous interplanetary magnetic field measurements from a second spacecraft. This is the approach used in the present paper where both interplanetary and magnetosheath data from the geocentric spacecraft Explorer 28 (IMP3) and Explorer 33 (IMP D) are available for comparison with that of Pioneer 7.

The trajectories of the three spacecraft for four days of September are presented in Figure 1. The top portion of Figure 1 shows the orbit projected on the solar ecliptic XY plane and the lower portion shows the view on the XZ plane. Explorer 28 (launched May 29, 1965, apogee ≈ 37 R_E, Period ≈ 6 days) is near the earth-sun-line on the sunward side of the earth. In the data to be presented below, Explorer 28 was always located in the interplanetary medium. Explorer 33 (launched July 1, 1966, with apogee ≈ 80 R_E, period $\approx$ 2 weeks) was near apogee but in the magnetosheath, approximately 60 R_E behind the earth during the four day interval September 26-29, 1966. The numbered dots on the trajectories in Figure 1 denote the beginning times of the days of September. The Pioneer 7 trajectory at 900-1000 R_E is shown for intervals when probable earth-associated effects were seen (see next section). A theoretical tail with a diameter of 40 R_E has been drawn in Figure 1 at an aberration angle of 5°. Note that the Pioneer 7 distance above the ecliptic plane of 26 R_E puts the spacecraft just outside of this average theoretical tail region.

Explorer 28 carried two monoaxial fluxgate magnetometers of the type flown on IMP's 1 and 2 (Ness et al., 1964; Fairfield and

Ness, 1967) which were designed to independently measure the vector field at 40.95 second intervals. A measurement should then have been obtained every 20.5 seconds however, one of these magnetometers failed to operate on Explorer 28 and consequently a field measurement is obtained every 40.95 seconds. A triaxial fluxgate magnetometer on Explorer 33 made vector measurements every 5.119 seconds (Behannon, 1968) and a monoaxial fluxgate on Pioneer 7 produced a vector measurement approximately every 1.3 seconds.

II. Results

Simultaneous data from the three spacecraft on September 26-29 are presented in Figures 2-5. The field magnitudes F, solar ecliptic latitudes angle θ and longitude ϕ are grouped together with the numbers 7, 33, and 28 referring to Pioneer 7, Explorer 33 and Explorer 28 respectively. Individual 40-second data points have been plotted for Explorer 28 and 80 second and 30-second averages have been plotted for Explorer 33 and Pioneer 7 respectively. A time scale in hours UT is shown, but the data from Explorer 33 and Pioneer 7 have been shifted to the left to allow for a time delay due to convection of the fields from one spacecraft to the next. The amount of the time shift has been chosen to achieve the best correspondence of discontinuities (Burlaga, 1967) observed at the three spacecraft. Explorer 33 data have always been shifted 25 minutes and Pioneer 7 data have been shifted 4:15, 4:05, 3:15, 3:00 in Figures 2-5 respectively.

Magnetic Field Convection

Similarity of the fields measured at the three spacecraft can best be seen in Figure 4. Many large variations in the latitude angle θ are present on this day and all of the features occurring on a time scale greater than 30 minutes appear at all three spacecraft. The longitude angles, ϕ, also agree very well, although it should be pointed out that as the latitude angle approaches 90° the azimuthal angle ϕ becomes less significant. Even features such as those at 4:15 and 20:10 in Figure 3 which occur on a time scale of a few minutes can often be tentatively associated at the three spacecraft.

This agreement of events at two spacecraft had previously been noted for large scale features at different heliocentric longitudes (Ness, 1966) and for small scale features with smaller satellite separation distances (Fairfield, 1967). The observations presented here extend these results to smaller scale events at large separation distances.

Delay times calculated from the arrival of discontinuities at the near earth spacecraft and at Pioneer 7 can be calculated from this simultaneous data. The satellite separation distances are accurately known and a velocity $\frac{\Delta X}{\Delta t}$ can be computed from the measurements. (ΔX = the X component satellite separation distance and Δt = the delay time). Since all spacecraft are near the earth sun line, approximately the same element of plasma passes over all spacecraft and the spacial orientation of a surface at discontinuity (Fairfield 1967) does not affect the result. The velocity has been calculated for numerous discontinuities in the interval September 26-29, and the results are plotted in Figure 6. The solid circles represent velocities calculated from Explorer 28 - Pioneer 7 observations and the open circles indicate the results from Explorer 33 - Pioneer 7 data. Independent measurements from the Vela 3 plasma probe (E. W. Hones, private communication) are designated by crosses. These preliminary Vela values are the velocity equivalents of the peak-counting-rate energy channels and they will probably agree with more refined values within 10 Km/sec. A sudden commencement storm at 15:30 on September 27 was followed by the velocity increase apparent in Figure 6 which is responsible for the progressively decreasing Pioneer 7 time shifts in Figures 2-5. The good agreement between the Figure 6 velocities obtained in these different ways confirms the concept that interplanetary fields frozen in the solar wind are convected outward from the sun.

Another interesting phenomena which can be noticed in Figures 2-5 is the relationship between the field magnitude observed in interplanetary space and that in the region near the geomagnetic tail at 1000 R_E. Except when Pioneer 7 is observing tail-related effects, the field magnitude at Pioneer 7 is consistently 1-4γ less than the undisturbed interplanetary field at Explorer 33. The difference occurs for various field orientations and, therefore, can not be an instrumental effect due to erroneous zero levels of the magnetometer sensors. This result is in agreement with the theoretical magneto-gasdynamic results of Dryer and Heckman (1967) and Alksne (1967) who predict magnetosheath fields lower than the interplanetary fields in a region near the geomagnetic tail, particularily at large negative X_{SE} positions.

Geomagnetic Tail Observations

The one interval of disagreement among the three spacecraft in Figure 4 occurs from 16:15 - 17:00 when Explorer 33 briefly enters the geomagnetic tail and assumes the high magnitude and anti-solar direction characteristic of the southern hemisphere of the tail. This illustrates the type of effect one would hope to see if Pioneer 7 entered the tail at 1000 R_E. No such effects are seen at Pioneer 7 in Figure 4, but they are found in Figures 2, 3 and 5 at times indicated by dark lines above the Pioneer 7 theta trace.

The most prominent example of Pioneer 7 observations of geomagnetic tail effects can be seen in Figure 3 from 13:00 - 14:00 Explorer 28 UT on September 27. At this time the field is very steady, oriented in the anti-solar direction, and its magnitude is twice the value of the interplanetary field. This observation of southern hemisphere field lines requires that the tail be tilted upward so that it intersects the northerly position of the spacecraft. A northward value of θ at Pioneer 7 at this time of approximately 6° is consistent with this interpretation. In the several hours preceeding 13:00 Explorer 28 UT on this day, there are other occasions when the field is oriented at $\phi = 180^{\circ}$ or 360°. The abrupt transitions between these opposing orientations (particularly 11:50, 12:15 and 12:30) are similar to neutral sheet crossings commonly observed nearer to the earth when the spacecraft passes through the point which divides the lines originating in the northern and southern hemispheres. This example then, suggests that a neutral sheet may still exist at 1000 R_E, as was pointed out by Ness et al. (1967) who discussed this particular event. Orientation of the interplanetary data between 12:00 and 15:00 on this day is rather different from that observed during the remainder of this day and the directions vary over a rather wide range. Explorer 33 data on September 27 is taken entirely within the magnetosheath and is similar to the interplanetary Explorer 28 data.

In Figure 2 the changes observed in Ø and F at Pioneer 7 between 5:30 and 6:45 are not seen in the interplanetary medium and probably denote an interval when Pioneer moves in and out of the lower half of the tail. Again from 10:15 to 11:40 anomalous effects in F, θ and Ø are seen at Pioneer 7. Although the field does not assume so perfect a tail orientation, the direction is near the tail orientation during several intervals between 10:15 and 11:40 and is clearly different from the interplanetary field. From 12:15 to 12:40 another clear case of tail-type orientation with an enhanced magnitude occurs. Again from 13:15 to 13:30 three brief intervals of tail-type orientation occur which are not related to any corresponding features at Explorer 28. After 13:30 there is very good correspondence among the three spacecraft indicating an absence of tail associated effects at Pioneer 7. Explorer 33 is always within the magnetosheath on this day.

Finally in Figure 5, tail effects are seen at Pioneer 7 from 11:50 - 13:00 and during several intervals from 16:10 - 24:00. At times such as 17:55 - 18:30 when Pioneer 7 is briefly outside the tail, the field magnitude is slightly reduced. From 21:30 to 23:10 Pioneer 7 appears to be primarily in the southern hemisphere of the tail and near the neutral sheet where the field is quite weak and variable. Explorer 33 is in the tail on September 29 except for brief intervals which are readily discernable in the figure.

The identifications of the tail cited above are not all obvious nor are they all certain, but they do tend to be supported by coarse preliminary comparison with data from the MIT plasma experiment

(Lazarus, private communication). This comparison shows that hours with anomalous plasma spectra generally correspond to hours when tail effects are observed in the magnetic field data.

The observations presented in Figures 2-5 indicate that there are numerous and relatively brief intervals of time when tail-associated effects are seen at Pioneer 7. The new technique of comparing measurements from several satellites confirms those cases cited by Ness et al. (1967b) and allows the identification of additional tail-associated phenomena. This realization that tail phenomena occur even more frequently than was originally apparent, reenforces the conclusion of these authors that the tail is either filamentary or is exhibiting considerable motion. The fact that the tail phenomena were observed over a period of at least six days indicates that time variations in the tail orientation are important at least on this time scale of days. The fact that the southern half of the tail was seen about as often as the northern half, despite the northerly position of the spacecraft, also indicates great variability in the tail orientation

As summarized in the introduction, one cause of time variations in the tail orientation is the known variability in the solar wind direction. A second possible cause of orientation changes is that discussed by Walters (1964) who investigated the variation in the direction of plasma flow across the earth's bow shock. Walters concluded that the direction of the interplanetary field influences the direction of flow of the shocked interplanetary plasma in the magnetosheath. This means that the effective direction of the solar wind as seen by the magnetosphere and tail is influenced by the interplanetary field direction. The magnitude of this deflection depends on the ratio of directed solar plasma energy to magnetic field energy and is of the order of 4° for typical solar wind parameters. A one degree change in solar wind direction corresponds to a 17 R_E change in the position of the tail at 1000 R_E. Rapid changes in field orientation are known to occur and this could have an important effect in producing rapid variations in the tail orientation.

Some support for Walter's idea may be obtained from Figures 2-5. The measurements of these figures are from a negative interplanetary sector (Ness and Wilcox, 1965) where the field is pointed generally toward the sun. Only during the intervals 11:00 - 14:00 on September 26 and 12:00 - 15:00 on September 27 does the field direction vary enough to range outside the negative sector region for an appreciable time interval. During each of these time intervals some of the clearest observations of the tail and associated neutral sheet crossings were observed. It can also be seen in the figure that most of the tail observations correspond to periods of negative interplanetary θ angle. Using Walter's interpretation, a negative θ angle in a negative sector will give a northward component to the effective solar wind direction and make observation of the tail at the northward position of Pioneer 7 more likely.

Ness et al. (1967) noticed that the Pioneer 7 tail observations frequently occurred between 15:00 and 21:00 UT when position of the diurnally varying dipole would tend to raise the tail above the ecliptic plane nearer to the northerly position of the spacecraft. Results of the further analysis presented above, however, reveal several tail observations at other times. Thus it appears that while the dipole position may exert some influence on the probability of observing the tail at Pioneer 7, the direction of plasma flow discussed above is a more important consideration.

Direct simultaneous observations of the plasma flow direction should yield additional information on the tail orientation. Further knowledge about the neutral sheet and possible filamentary structure of the tail at 1000 R_E will also be obtained by further comparison of simultaneous plasma and magnetic field data.

III. Summary

Analysis of simultaneous magnetic field measurements in the interplanetary medium in front of the earth and in the magnetosheath near the earth-sun-line 60 to 1000 R_E behind the earth have revealed interesting features of the solar wind and the geomagnetic tail. Discontinuous magnetic field features seen by Explorer 28 in the interplanetary medium are generally observed at Pioneer 7 from 3 to 4½ hours later. Velocities computed from these delay times agree with values of solar wind velocity observed by the Vela 3 spacecraft and support the concept that magnetic fields frozen in the solar wind are convected past the two spacecraft. Comparison of the corresponding fields measured in interplanetary space and at 1000 R_E shows that the latter magnetosheath fields are consistently lower than the undisturbed interplanetary values. This result is in agreement with the predictions of the theoretical magnetogasdynamic models of the solar wind-geomagnetic field interaction.

On numerous occasions the magnetic field at 1000 R_E assumed a solar or anti-solar directional orientation which was different from that measured simultaneously in interplanetary space. Field magnitudes behind the earth were typically several gammas larger than the adjacent magnetosheath values and this fact contributed to the interpretation of the results as observation of the geomagnetic tail. Occasional 180° reversals in the tail field direction also suggest that the tail neutral sheet is still present at 1000 R_E. From the facts that (1) the intervals of tail observations were relatively short (typically 15 minutes to 4 hours), (2) the intervals were observed during a period of 6 days, and (3) both northern and southern halfs of the tail were observed, it is argued that the geomagnetic tail frequently changes its orientation and sweeps across the spacecraft. It is suggested that the tail orientation is changed by both real variations in the solar wind direction and effective changes in this direction caused by the magnetic field direction affecting the flow through the bow shock. An alternate possibility that the tail at 1000 R_E has a filamentary structure is also suggested.

Acknowledgements

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Figure Captions

Figure 1 Trajectories for the three satellites Explorer 28, Explorer 33, and Pioneer 7 are shown projected in the solar ecliptic XY plane (top) and XZ plane (bottom) for the four day interval September 26-29, 1966. A theoretical magnetic tail of diameter 40 R_E has been shown at a 5^o aberration angle for comparison with the Pioneer 7 measurements at 900-1000 R_E behind the earth.

Figure 2 Simultaneous magnetic field measurements at the satellite Explorer 33, Pioneer 7 and Explorer 28 are shown. Field magnitude F, solar ecliptic latitude angles θ and longitude angle ϕ are grouped together and marked with the number of the satellite. The time scale in hours UT on September 26, 1966 corresponds to the Explorer 28 data. Pioneer 7 data has been shifted 4 hours and 15 minutes to the left and Explorer 33 data 25 minutes to the left to make the field discontinuities correspond at the three spacecraft. Periods of probable tail observation at Pioneer 7 are designated by solid lines above the θ trace.

Figure 3 Simultaneous magnetic field measurements on September 27, 1966 are shown in a format similar to Figure 2. Pioneer 7 data has been shifted 4 hours and 5 minutes to the left and Explorer 33 data 25 minutes to the left. Intervals of tail-associated effects have been marked by solid lines above the Pioneer 7 theta trace between 10:00 and 15:00.

Figure 4 Simultaneous magnetic field measurements on September 28, 1966 are shown in a format similar to Figure 2. Pioneer 7 data has been shifted 3 hours and 15 minutes to the left and Explorer 33 data 25 minutes to the left. Fields at the three satellites agree very well on this day and suggest that tail effects were absent at Pioneer 7. Explorer 33 was in the tail between 16:00 and 17:00.

Figure 5 Simultaneous magnetic field measurement on September 29, 1966 are shown in a format similar to Figure 2. Pioneer 7 data has been shifted 3 hours to the left and Explorer 33 data 25 minutes to the left. Four intervals of tail associated effects at Pioneer 7 have been designated by solid lines above the θ values between 1200 and 2400 hours.

Figure 6 Velocities are shown which were computed from the delay times in the arrival of field discontinuities at the near earth spacecraft and Pioneer 7. Explorer 28 - Pioneer 7 velocities are designated by solid circles and Explorer 33-Pioneer 7 velocities by open circles. Velocities from the Vela 3 plasma experiment are indicated by crosses. A sudden commencement storm at 15:30 on September 27 is followed by a gradual 200 km/sec increase in the velocities measured by these different methods.

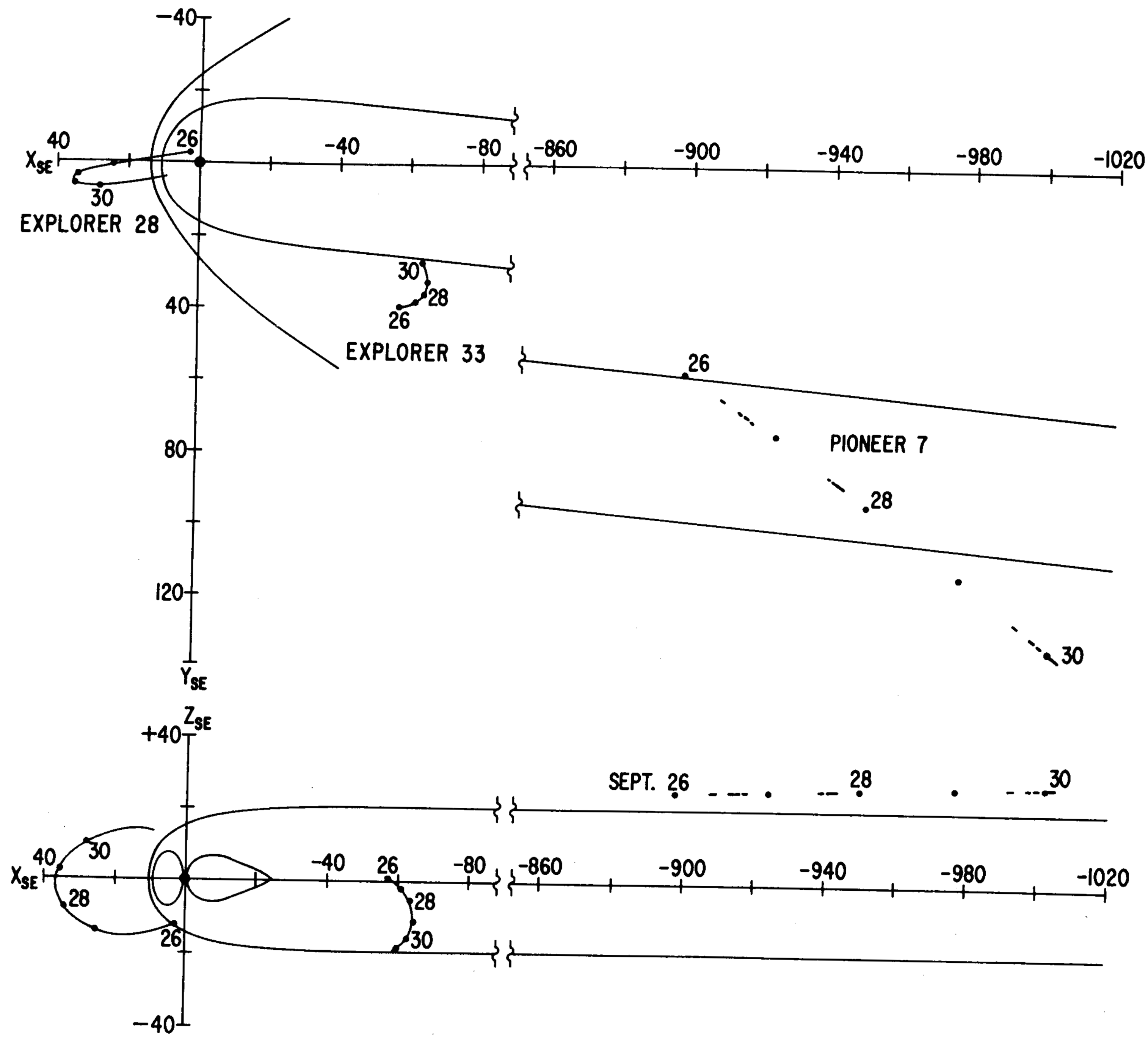
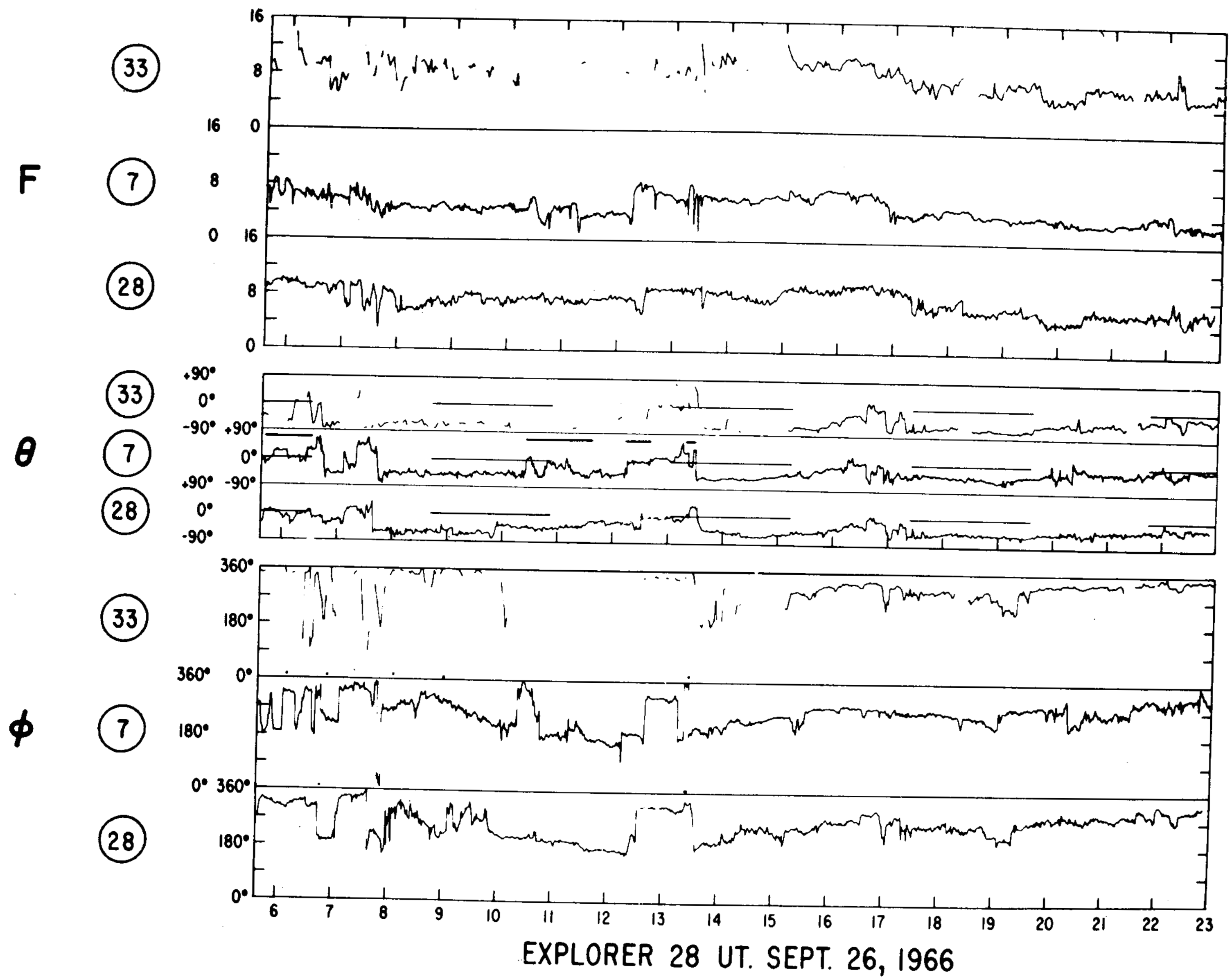


FIGURE 1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EXPLORER 28 UT. SEPT. 26, 1966

FIGURE 2

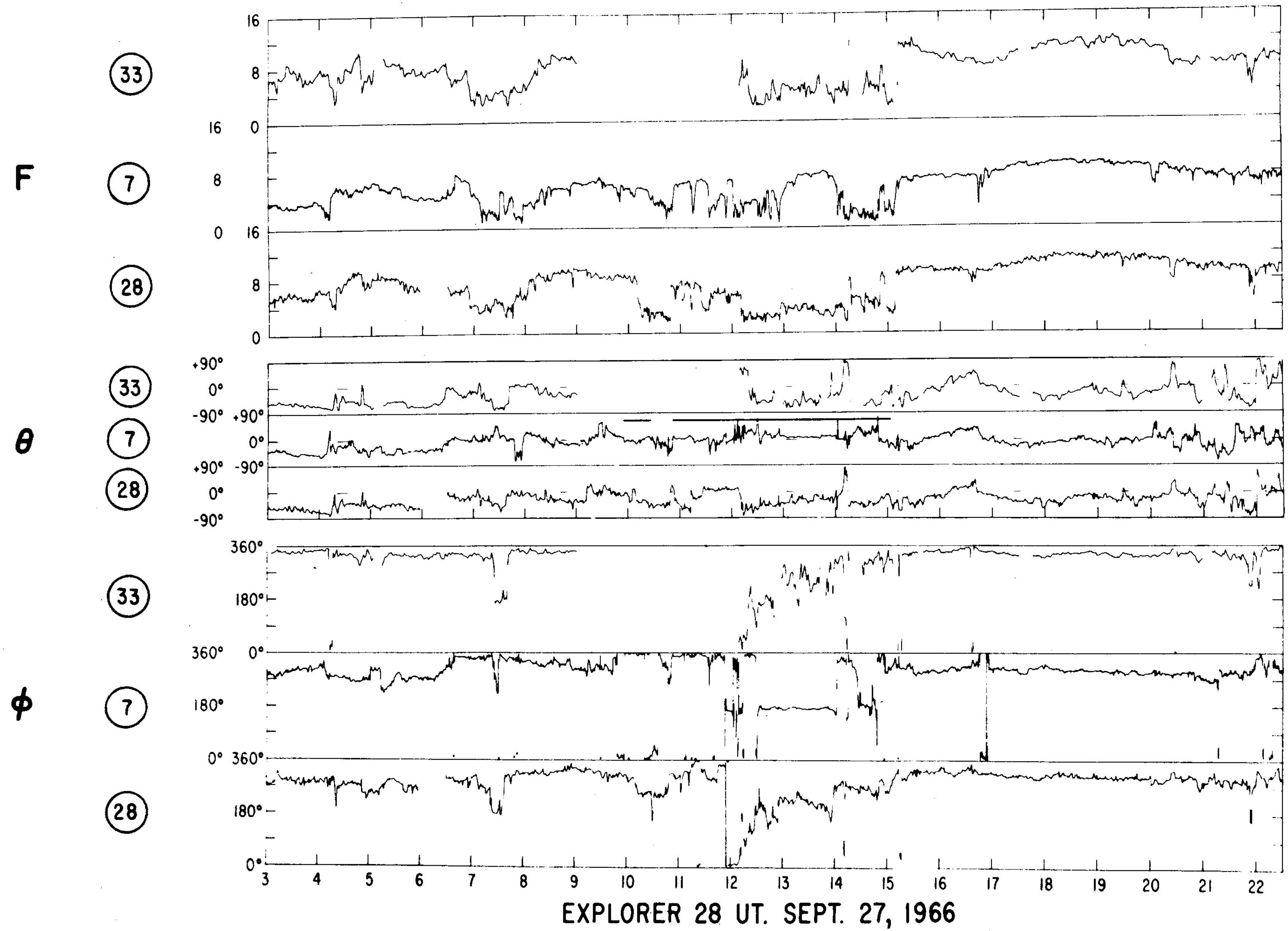
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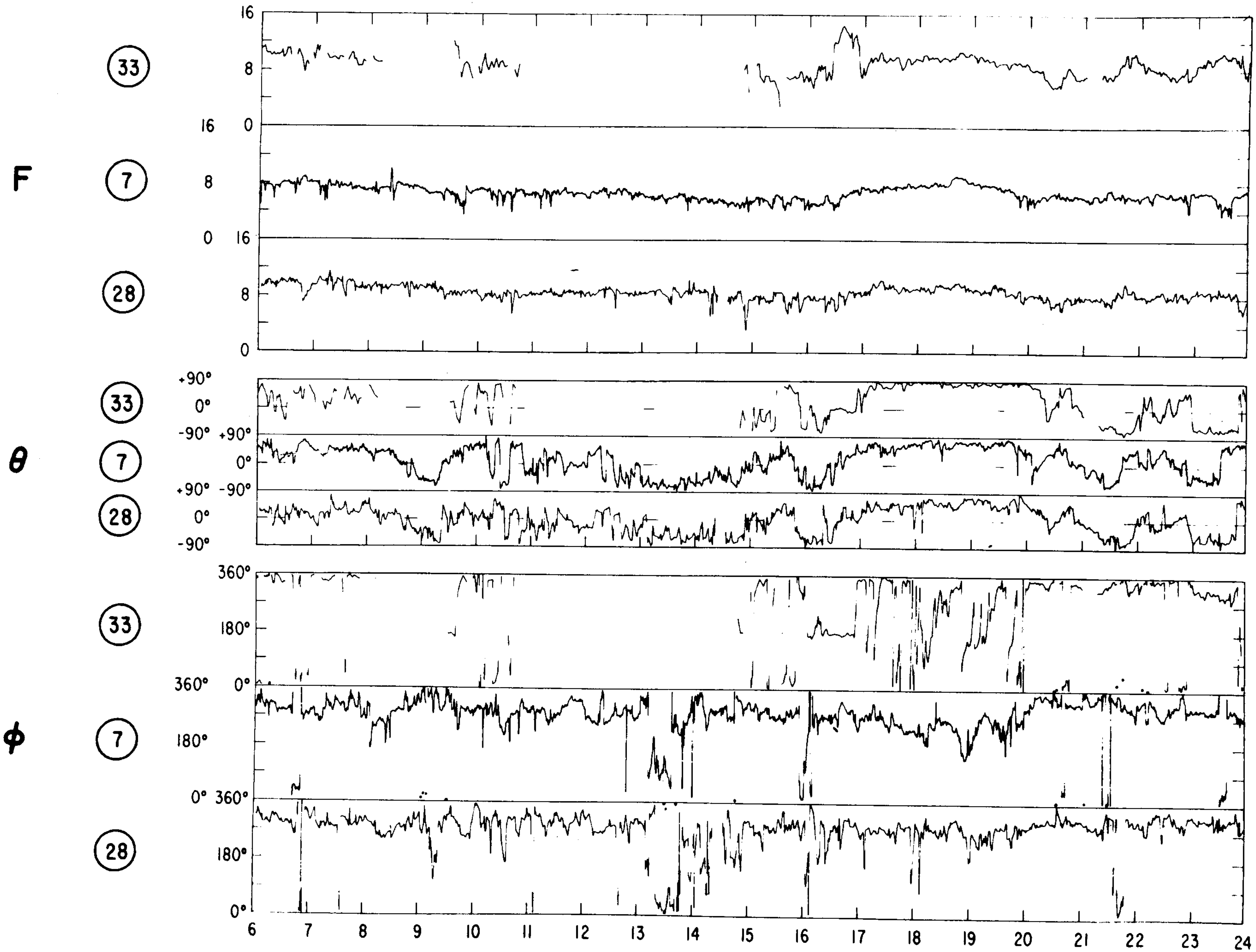
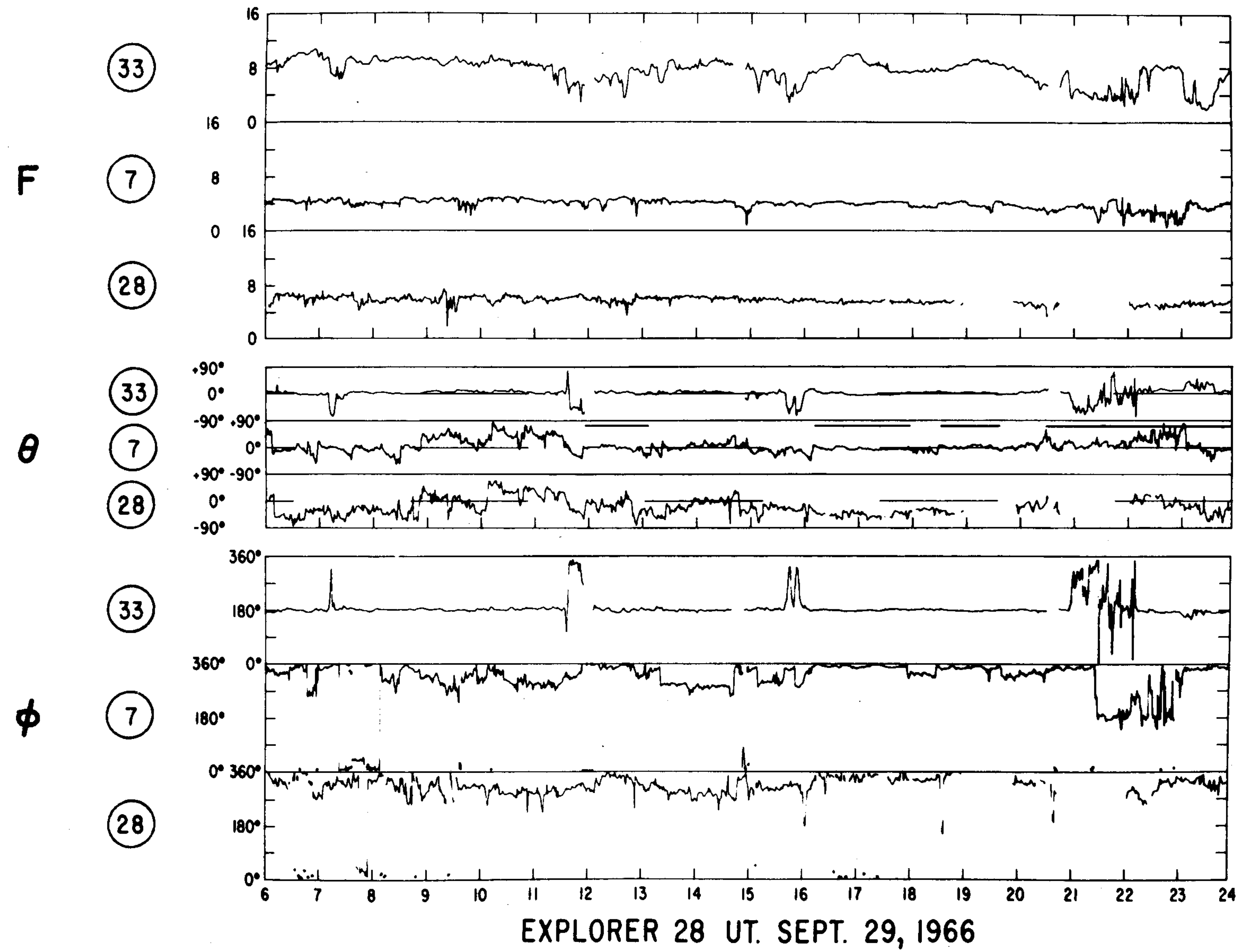
FIGURE 3



EXPLORER 28 UT. SEPT. 28, 1966

FIGURE 4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EXPLORER 28 UT. SEPT. 29, 1966

FIGURE 5

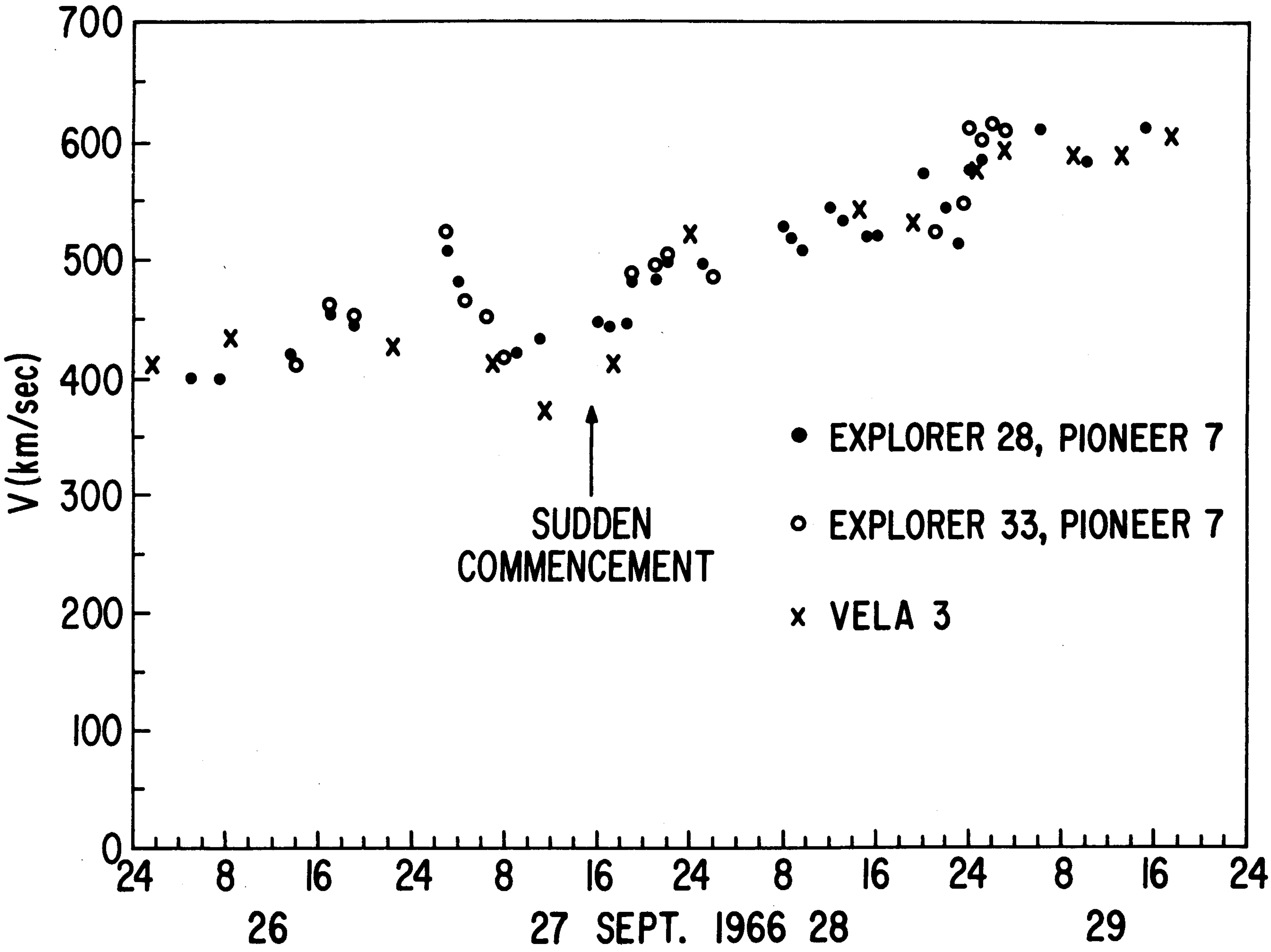
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FIGURE 6